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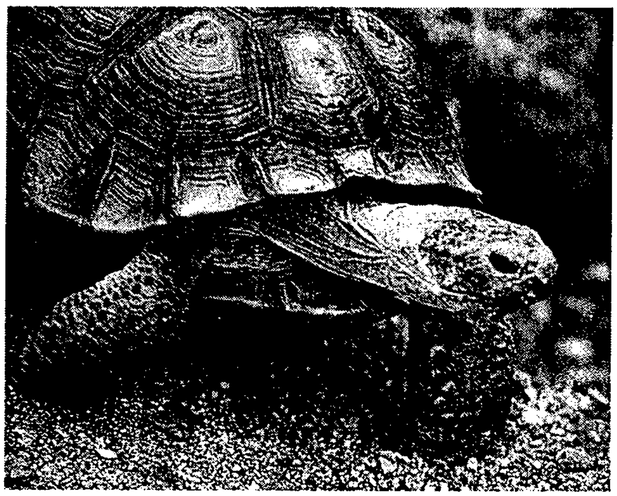
Simulating Land Use Alternatives and Their Impacts on Desert Tortoises at Fort Irwin, California

by Jocelyn L. Aycrigg, Steven J. Harper, and James D. Westervelt



The U.S. Army Construction Engineering Research Laboratories (USACERL) has developed a series of models to study the processes involved with building dynamic landscape simulations (DLS). This DLS model applies to a desert tortoise population (a Federally listed threatened species) at Fort Irwin, CA, which has been the Army's National Training Center since 1979. This report demonstrates new methods available to assess the impacts of military training at Fort Irwin across time and space on desert tortoises and their habitat.

Recently, efforts in computer-based simulation have been directed towards developing spatially explicit models, but the spatial distribution and complexity of land characteristics make it difficult to analyze and simulate a landscape as a whole. Partitioning a landscape into small but connected parcels makes it possible to work with patches of land that can be treated as homogeneous for certain analyses. This approach seems especially useful for developing spatially explicit models for endangered species on military lands.

The results of this model demonstrates how to evaluate the potential effects of military training on desert tortoises and their habitat. These results are not expected to provide land managers with detailed predictions of specific impacts, but do demonstrate the feasibility of using this modeling approach to develop landscape-level simulations.

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13. ABSTRACT (Maximum 200 words)

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Foreword

This study was conducted for U.S. Army Corps of Engineers (USACE) under Project 4A161102BT25, "Environmental Research-Corps of Engineers"; Work Unit LLJ07, "Spatial Simulation Modeling Applications for TES." The technical monitor was Dr. Thomas Hart, CERD-M.

The work was performed by the Natural Resource Assessment and Management Division (LL-N) of the Land Management Laboratory (LL), U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL principal investigator was Dr. James D. Westervelt. Jocelyn L. Aycrigg had an appointment in the Research Participation Program at USACERL in conjunction with Oak Ridge Associated Universities and is currently at the Illinois Natural History Survey, Champaign, IL. Dr. Steven J. Harper is a post-doctoral researcher working at USACERL through Oak Ridge Associated Universities. Thanks to William F. Seybold, a research assistant at Colorado State University working at USACERL, for his many helpful comments, which improved this report immensely. Robert Lacey is Acting Chief, CECER-LL-N, Dr. John Bandy is Acting Operations Chief, CECER-LL, and William D. Goran is the Technical Director of Conservation. The USACERL technical editor was Linda L. Wheatley, Technical Information Team.

COL James A. Walter is Commander of USACERL, and Dr. Michael J. O'Connor is Director.

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1 Introduction

Background

Fort Irwin, CA, is situated midway between Los Angeles, CA, and Las Vegas, NV, in the center of the Mojave Desert (Figure 1). Since 1979, Fort Irwin has been the Army's National Training Center, which provides large areas for force-on-force military training. The desert tortoise, a Federally listed threatened species, lives within the boundary of Fort Irwin and throughout the Mojave Desert ecosystem. It is a long-lived species with a low reproductive rate and a patchy distribution, which makes it vulnerable to perturbation (Woodman et al. 1986).

During January 1993 through June 1995, the U.S. Army Construction Engineering Research Laboratories (USACERL) developed a dynamic landscape simulation model of a desert tortoise population at Fort Irwin, CA (Westervelt et al. 1997). This model is one of a series of models developed by USACERL to study the processes involved with building landscape simulations. Researchers continue to learn ways to enhance and improve these types of models. This report attempts to assess the impacts of military training across time and space on desert tortoises (*Gopherus agassizii*) and their habitat.

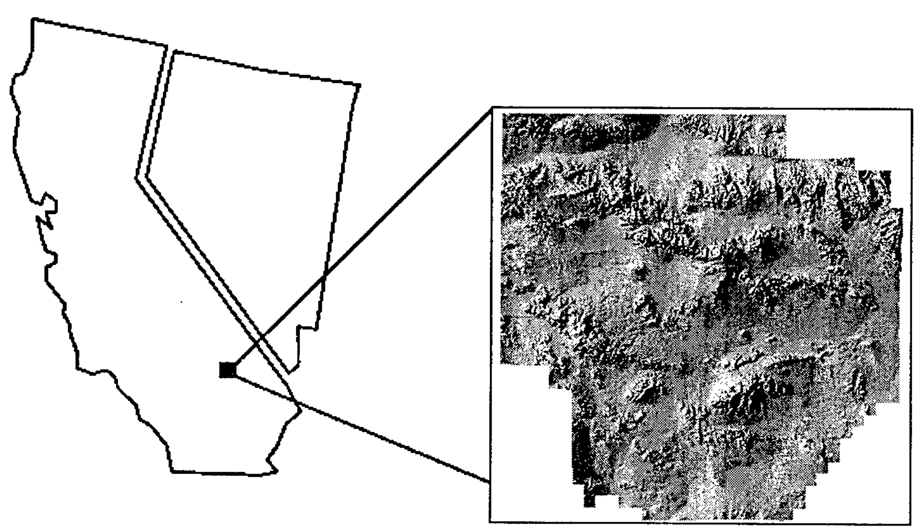

Figure 1. Location of Fort Irwin, CA.

Computer-based simulation modeling is becoming an increasingly important tool for government. It can provide insights into species-habitat relationships, patterns of habitats in space and time, and the effects of impacts on animal populations and their environments (Turner et al. 1995). Recently, efforts have been directed towards developing spatially explicit models (Turner et al. 1995), but the spatial distribution and complexity of land characteristics makes it difficult to analyze and simulate a landscape as a whole. Partitioning a landscape into small but connected parcels makes it possible to work with patches of land that can be treated as homogeneous for certain analyses (i.e., gridded landscape models). Such an approach seems especially useful for developing spatially explicit models for endangered species on military lands.

Objective

The primary goal of this research was to introduce military installation managers to dynamic landscape simulation (DLS) for predicting the results of human interactions with the environment. A DLS is initialized with system state information, typically captured in a geographic information system (GIS) and predicts future states through simulation models that capture the system's dynamic interactions. To demonstrate the potential of DLS, a simulation model was developed for desert tortoises at Fort Irwin, a real and familiar landscape. This model can create a snapshot of the landscape which represents their distribution at a given time. DLS uses the snapshot as a starting state and allows information regarding the position of each tortoise (e.g., location of females in relation to males and distance to nearest food, water, and cover) to determine how the tortoises will move around on the landscape until another snapshot is taken. This process can occur repeatedly through time so that a dynamic landscape is simulated. Our snapshot of the landscape can be created in a geographic information system (GIS). Combining GIS data with a dynamic landscape provides a powerful tool for evaluating alternative land-use strategies.

The secondary goal of this study was to use the desert tortoise model developed by Westervelt et al. (1997) to evaluate the potential response of tortoise density and habitat suitability to changes in the intensity, location, and timing of military training. This model, like all management models, is useful only when local land managers participate in and guide the development of it. USACERL researchers are confident that this model can be the foundation of a new tool for management of desert tortoise landscapes.

Scope

This study serves as a scientific investigation of the sensitivity of the developed model to these simulated variations. It is not intended to provide land managers with absolute predictions of the response of tortoise density or habitat to different land management approaches. At best, the results could be viewed as suggestive of the trends that might be expected as training intensity is changed both temporally and spatially. The goal was to evaluate the model's ability to predict results of various military training activities. The results should be verified through the observations of land managers and controlled field experiments.

Approach

Simulation models developed for land managers are intended to predict the results of land management practices (in our case, variations in military training) before implementation. To assess the model's response to various training activities, alternative simulation scenarios were created. A series of scenarios were used to discover the tortoise density and habitat trends associated with altering the location and timing of military training.

The Fort Irwin landscape was divided into 1 km^2 grid cells, with a total of 3,249 cells representing the entire installation. The basic processes or cell model were run in each cell, with only the initialization values differing among cells. The model simulated changes through time using mathematical equations. The state of any given cell was a function of its state in the previous time step, the state of adjacent neighbors in the previous time step, and external weather factors.

The cell model was developed as four major submodels:

- climate (including soil moisture and temperature)
- vegetation
- tortoise population dynamics
- tortoise dispersal movements.

Multidisciplinary teams used a variety of software to develop these submodels, based on literature (Westervelt et al. 1997) and the research of desert tortoises in the Mojave Desert conducted by Krzysik (1991 and 1994). Westervelt et al. (1997) discusses each of the submodels in detail.

A fifth submodel was developed to incorporate military training into the simulation model. Direct impacts on tortoises by military training (i.e., crushed by a vehicle) were determined to be small in relation to indirect impacts (Krzysik 1994); therefore, direct impacts in the model were not included. Indirect impacts (i.e., vegetation destruction and increased soil compaction caused by off-road vehicles) have detrimental effects in desert environments (Bury et al. 1977, Adams et al. 1982, Webb, Steiger, and Wilshire 1986). No data indicating the impacts of military training on tortoise habitat were available; therefore, the assumption was made that military training caused impacts similar to off-road vehicles. Furthermore, as a surrogate for a detailed map of training locations, a soil compaction map was developed from elevation data, by assuming that training occurs most often in lower elevations (Krzysik 1994). The response of the tortoise population to changes in the timing, location, and intensity of training was simulated.

Mode of Technology Transfer

Lessons learned in the research for this modeling simulation approach and underlying software are being applied to other sites.

2 Experimental Design

The Model

The USACERL-developed simulation model was used to model tortoise populations over a 250-yr period. Parameters of the model were altered to show what might happen under a variety of conditions. Each set of parameters was manipulated and evaluated in a separate submodel. Each submodel had a 1-month time step, which accommodated seasonal changes within the landscape such as weather patterns, tortoise nesting and egg-laying seasons, and vegetation growth cycles. All simulations were initiated in January (time step 0).

A grid cell size of 1 km^2 was used for analyses because desert tortoises have home ranges that extend up to 1 km^2 (Krzysik 1994). The dispersal of tortoises in the model was represented by movement from one grid cell to a neighboring cell in any of the four cardinal directions.

Only females were modeled because a sex ratio of 1:1 was assumed (see Berry 1976). Doak, Kareiva, and Klepetka (1994) and Luke (1990) found that the rate of population growth relies largely on the survival of large adult females. The total tortoise population on the simulated landscape was obtained by doubling the total number of female tortoises.

A brief discussion of each of the five submodels follows. However, more specifics about the model and data used in the model can be found in Westervelt et al. (1997).

Climate Submodel

The purpose of this submodel was to determine monthly soil moisture, monthly surface temperature, and to estimate water available to tortoises. The approach allowed each month's mean temperature to vary within the appropriate historical values according to a normal distribution (Westervelt et al. 1997). Additionally, temperature was adjusted for physical conditions (i.e., slope and elevation), evapotranspiration was determined from the Thornwaite model (Thornwaite 1948), and infiltration and runoff of precipitation was estimated (Westervelt et al. 1997).

Vegetation Submodel

The purpose of this submodel was to determine vegetative cover and estimate available food. The approach estimated the total vegetative cover of a given cell, estimated seasonal changes in aerial cover using logistical equations, and determined community composition of annuals and perennials (Westervelt et al. 1997).

Tortoise Population Dynamics Submodel

The purpose of this submodel was to identify impacts of human activity and habitat quality on tortoise population dynamics. The approach captured demographic changes by subdividing the population into five life history stages (eggs, hatchlings, juveniles, adults, and elders). Population dynamics were simulated by incorporating transitions between life history stages, reproduction, and mortality of tortoises (Westervelt et al. 1997).

Tortoise Dispersal Movements Submodel

The purpose of this submodel was to simulate immigration, emigration, and costs associated with dispersal, as well as to investigate connectivity among subpopulations (Westervelt et al. 1997). Emigration was determined by conditions in the home cell. Emigration took place if conditions in one of the four adjacent cells were better than the home cell. The direction of dispersal was toward the adjacent cell with the best relative conditions. The submodel did not allow the dispersal of eggs or hatchlings.

Training Impacts Submodel

The purpose of this submodel was to determine the indirect impacts of military training on tortoise populations. Based on available literature (Krzysik 1994), indirect impacts of training (e.g., disturbance of vegetation and compaction of soil) were assumed to be more significant than direct impacts (e.g., getting crushed by a vehicle) so direct impacts were not included in the model.

In place of a detailed training map, which could not be obtained, a soil compaction map was developed from elevation data, by assuming that the most severe soil compaction occurs at lower elevations (Krzysik 1994). The indirect impact of training on tortoises was captured as a map of training intensity. The soil compaction map had values ranging from 4 to 17 kg/cm^2. These values were divided into three categories, which represented different training level intensities:

4.0-9.0 kg/cm^2 = low training

10.0-14.0 kg/cm^2 = moderate training

15.0-17.0 kg/cm^2 = high training

The training level intensities then were associated with different levels of tracked-vehicle-days per month (TVD/month). These values were determined from training data in Krzysik (1994).

1-475 TVD/month = low training

476-1189 TVD/month = moderate training

1190-1666 TVD/month = high training

A training intensity map was created by reclassifying the soil compaction map based on the above values (Figure 2). The training intensity was changed both temporally and spatially in our model simulations.

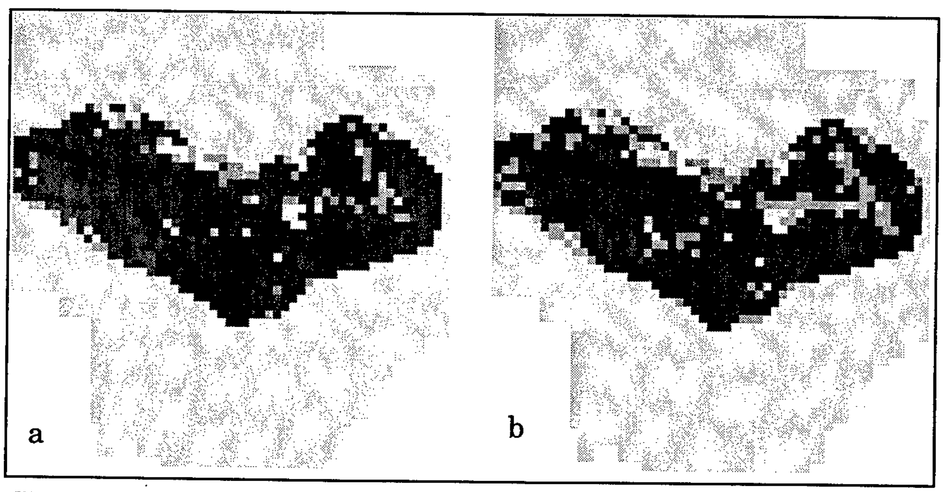

Figure 2. Soil compaction map (a) used to create training intensity map (b) for Fort Irwin. Lighter shades within the heart-shaped area indicate low compaction and low training intensity, while darker shades indicate high compaction and high training intensity. No soil compaction or training occurred on the remaining portion of the landscape.

Hardware and Software

A network of UNIX workstations, Macintosh computers, and IBM-compatible personal computers was used to conduct these simulations. The simulation model which applied to each cell in the landscape was applied using STELLA II,* a graphical programming language. This desktop modeling tool uses icons and schematics, linked with equations, as the mechanism to build the equations upon which the model is based.

To apply the simulation model across multiple cells, STELLA II equations were translated into C++ programs by the Spatial Modeling Environment (SME; Maxwell and Costanza 1993; Maxwell 1995). SME applies the same equations used in the single-cell STELLA II model, but it runs the equations within each cell of the landscape and generates output data layers. In other words, SME allows the model and all its functions to run dynamically in each cell across the Fort Irwin landscape and transfers information between cells. For this model, SME Version 2 was used.

Spatial Data

The initialization maps for the simulation model were created in the GIS program, Geographic Resource Analysis Support System (GRASS; USACERL 1993). Output data from SME were written to GRASS data layers.

The spatial data used for the climate submodel included average monthly available water content (AWC), which was generated using a deterministic run of the climate submodel. Vegetation maps were derived from Land Condition Trend Analysis (LCTA) transect data using a back-propagation neural network (Wu and Westervelt 1994). Tortoise density maps were obtained from transect data collected by Krzysik (1991, 1994) using a back-propagation neural network (Westervelt et al. 1997). Topography data were acquired from digital elevation models (DEM) which were used to derive slope and aspect maps. Westervelt et al. (1997) provides more specifics regarding these spatial data.

* STELLA II is a product of High Performance Systems, Inc., 400 Lyme Road, Suite 300, Hanover, NH 04755, (800) 332-1202.

Simulated Training Scenarios and Results

General Description

Each of 7 different training scenarios was simulated 100 times, with each run capturing changes over 250 years. The results shown here are the mean values for tortoise populations over the 100 runs. The scenarios differed in how vegetation and tortoise density input maps were derived as well as in training intensity maps. The model was altered for each scenario by changing input maps and model parameters. Model algorithms, time steps, spatial extent, and resolution were not changed between scenarios.

This research was intended to identify trends in tortoise density due to environmental responses to simulated changes in training intensity. Note that relative, rather than absolute, differences among scenarios should be compared.

Scenario 1: Neural Network Baseline

In scenario 1, the model was run with no new training after time step 0 to simulate changes in vegetation and tortoise density expected in 250 years. This run essentially simulated the recovery of the landscape from previous impacts. It also served as a final debugging of the model to ensure that all submodels were working as intended.

The initialization maps for tortoise density and vegetation were derived from tortoise transect data (Krzysik 1994) and LCTA transect data using a back-propagation neural network analysis (Figure 3). Wu and Westervelt (1994) contains more information on back-propagation neural network analyses, and Westervelt et al. (1997) contains more information regarding the derivation of these maps.

Tortoises were distributed across the landscape at moderate densities with higher concentrations along the southern boundary, while more vegetative cover occurred in the northwest portion of Fort Irwin (Figure 3). This approach produced an adequate representation of tortoise densities and vegetative cover at Fort Irwin, which was used to initialize the model (A. Krzysik, pers. comm.).

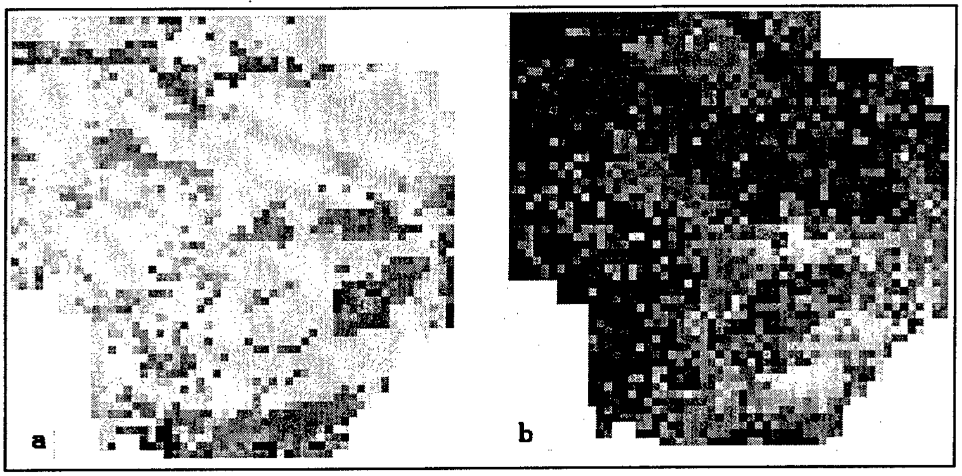

Figure 3. Initialization maps for desert tortoise density (a) and vegetation cover (b) used in scenario 1 for Fort Irwin. These maps were created using a back-propagation neural network analysis by correlating ground truth data with satellite imagery. Lighter shades indicate low tortoise density or less vegetative cover, while darker shades indicate high tortoise density and more vegetative cover.

After running the model 100 times, the results were averaged. They showed tortoises spatially distributed in highly concentrated patches across Fort Irwin (Figure 4). Woodman et al. (1986) found "core" areas where tortoise densities were higher than surrounding areas. Furthermore, Krzysik (1994) and Woodman et al. (1986) found a large tortoise concentration near the southern boundary of Fort Irwin, which is similar to our tortoise density maps at time 0 and 250 years (Figures 3 and 4). Nicholson et al. (1980) found a similar pattern of tortoise densities on the China Lake Naval Weapons Center, San Bernardino County, CA, with small pockets of high tortoise densities. Tortoise populations are naturally clumped on the landscape (Krzysik 1994).

Even though tortoises were distributed in patches, their density increased asymptotically over the 250 years. This increase might be expected given no additional training after time step 0, which allowed the landscape to recover from previous impacts. The results showed that tortoises concentrated in areas that had good vegetative cover (Figures 4 and 5a). The tortoises may have been moving away from unsuitable habitat rather than towards good habitat as has been observed in turtles (Gibbons 1986).

The simulated vegetative cover after 250 years differed little from the carrying capacity map (Figure 5). In the model, it was assumed that vegetation could not exceed carrying capacity. Instead, vegetation densities fluctuated just below carrying capacity.

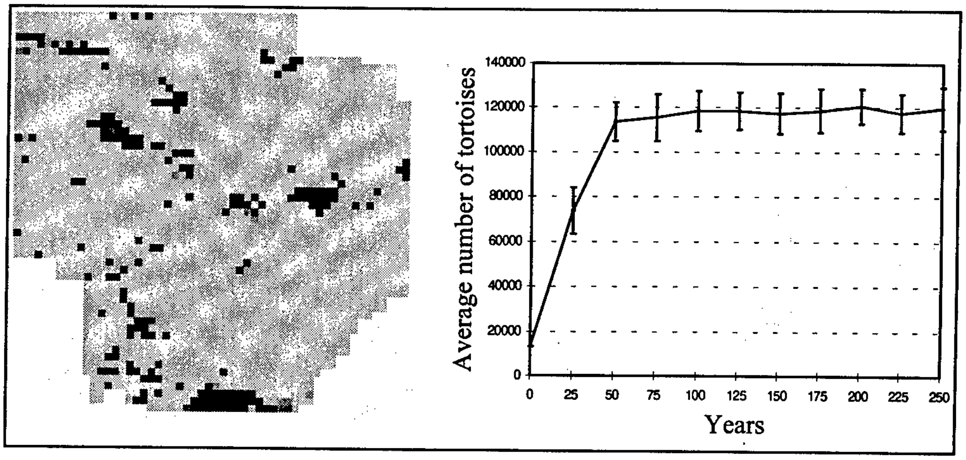

Figure 4. The average spatial distribution of desert tortoises and the change in average number of desert tortoises after running scenario 1 for 250 years for Fort Irwin. The average was obtained from 100 simulations of scenario 1. Scenario 1 used the back-propagation neural network analysis to derive initialization maps for tortoise density and vegetative cover (see Figure 3). No new training occurred in the model after time step 0. The tortoise population asymptotically increases over time, but becomes spatially distributed in highly concentrated patches (darker shades indicate higher tortoise densities).

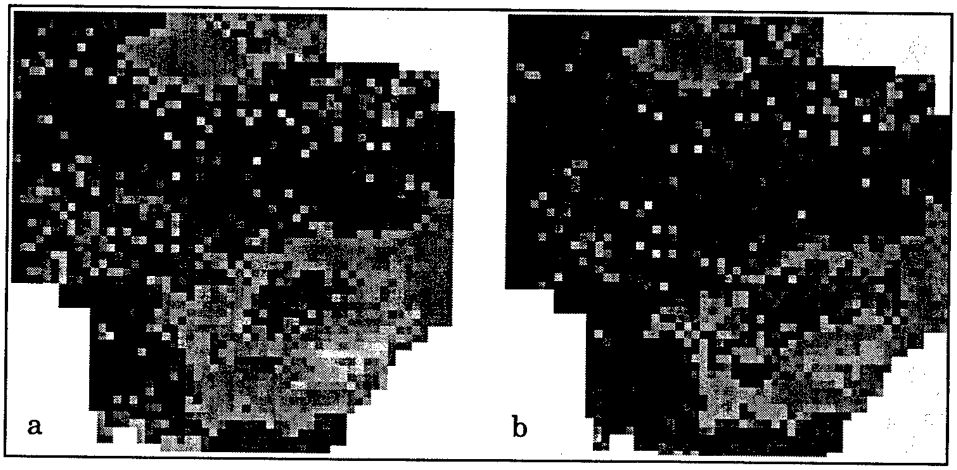

Figure 5. The average percent aerial cover of vegetation after running scenario 1 for 250 years (a) and the carrying capacity of vegetation (b) at Fort Irwin. The average was obtained from 100 simulations of scenario 1. No new training occurred in the model after time step 0. The simulated vegetation cover after 250 years (a) appears to be very close to carrying capacity (b). Darker areas represent higher densities of vegetative cover.

The habitat suitability index developed for tortoises in the model appeared to decrease over time (Figure 6). Habitat suitability was a function of the percentage of green vegetation available to tortoises for consumption and the percentage of total vegetative cover. Over time, the increase in tortoise densities caused greater amounts of green vegetation to be consumed and decreased the habitat suitability index.

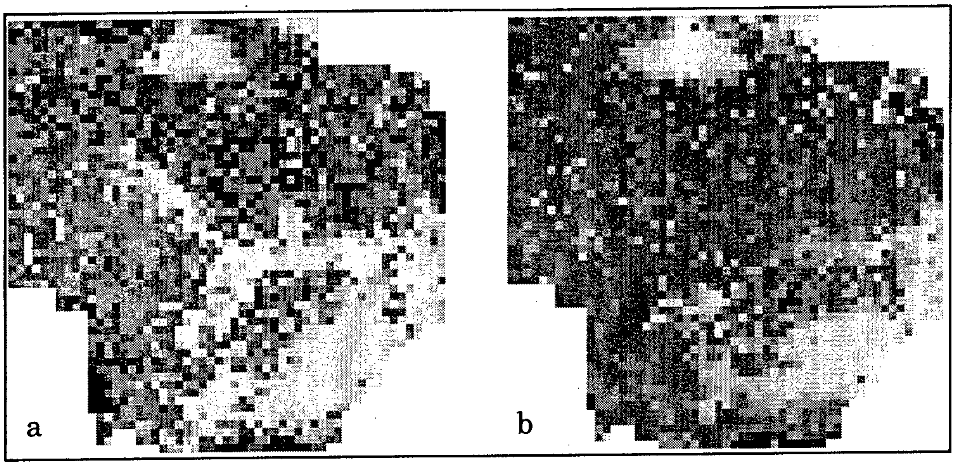

Figure 6. The average index of habitat suitability for desert tortoises after running scenario 1 for 250 years at Fort Irwin, for time 0 (a) and time 250 years (b). The average was obtained from 100 simulations of scenario 1. No new training occurred in the model after time step 0. Darker shades represent habitat better suited for tortoises.

Scenario 2: New Baseline

This simulation established a new baseline for scenarios 3 through 7. The maps for tortoise density and vegetation cover from the end of scenario 1 (Figures 4 and 5a, respectively) were used as the initialization maps for this scenario. The intention was to simulate a landscape that had recovered from training after 250 years and could be used as the initialization landscape for the remaining scenarios, which included training impacts. By using the output from scenario 1 the confounding effects of past training impacts were effectively removed, which allowed for a fairly reasonable assessment of the impacts of future training.

In scenario 1, the tortoise population stabilized, and throughout scenario 2 that population level was maintained (Figure 7). Furthermore, the spatial distribution of tortoises across Fort Irwin remained relatively constant: tortoise densities within cells changed only in response to environmental stochasticity (Figure 7).

In scenario 2, the initialization map for vegetation (Figure 5a) was very close to carrying capacity, and the vegetation changed very little over the next 250 years (Figure 8a). Furthermore, the habitat suitability remained relatively constant (Figure 8b). The results of this scenario indicated that a stable point was reached in the model and that the simulated landscape had recovered fully from training.

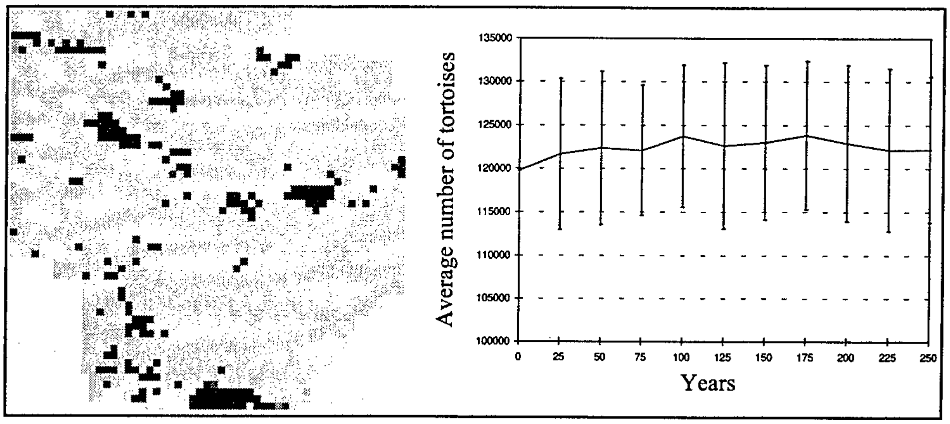

Figure 7. The average spatial distribution of tortoises and the change in average number of tortoises after running scenario 2 for 250 years for Fort Irwin. The average was obtained from 100 simulations of scenario 2. Scenario 2 used Figures 4 and 5a as initialization maps for tortoise density and vegetative cover, respectively. No new training occurred in the model after time step 0. The tortoise population remained relatively stable. Darker shades represent higher tortoise densities.

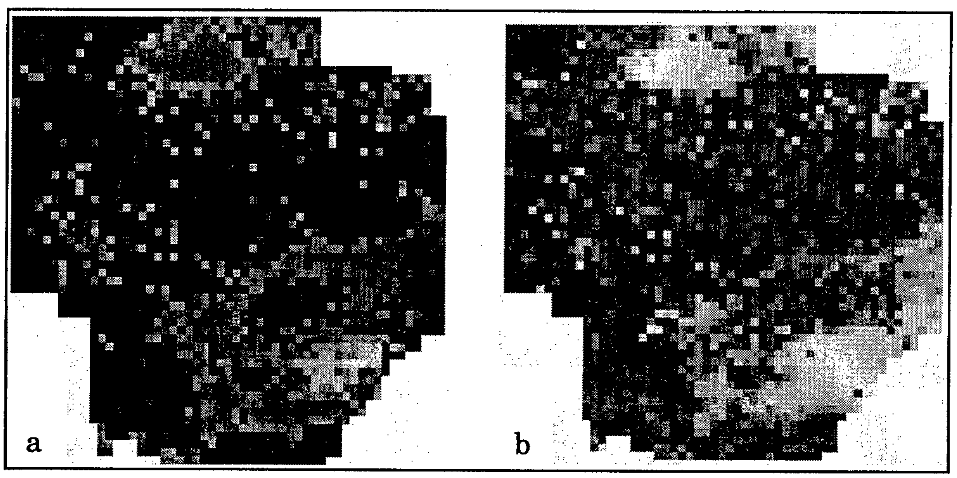

Figure 8. The average percent aerial cover of vegetation (a) and average index of habitat suitability (b) for desert tortoises after running scenario 2 for 250 years at Fort Irwin. The average was obtained from 100 simulations of scenario 2. Figures 5a and 6b show the average percent aerial cover of vegetation and index of habitat suitability, respectively, of time 0 for scenario 2. No new training occurred in the model after time step 0. Darker shades represent higher densities of vegetative cover (a) and habitat better suited for tortoises (b).

Scenario 3a: Low Training Intensity

In this and the following scenarios, the ability of the simulation model to respond to varying training intensities was evaluated. In this scenario, a low level of training intensity (237.5 TVD/month) was used at each time step (i.e., monthly) across all of Fort Irwin. The initialization maps for tortoise density and vegetation were the same used for scenario 2 (Figures 4 and 5a, respectively).

Our results show that the tortoise population did not recover from the training impacts, but stabilized at a lower value (Figure 9). Tortoises became restricted to a few small patches which contained high densities. Less vegetative cover was available for tortoises after 250 years (Figure 10) because the vegetation was unable to recover from monthly training events. The impacts of low intensity training were also evident in the habitat suitability index which decreased over time (Figure 10).

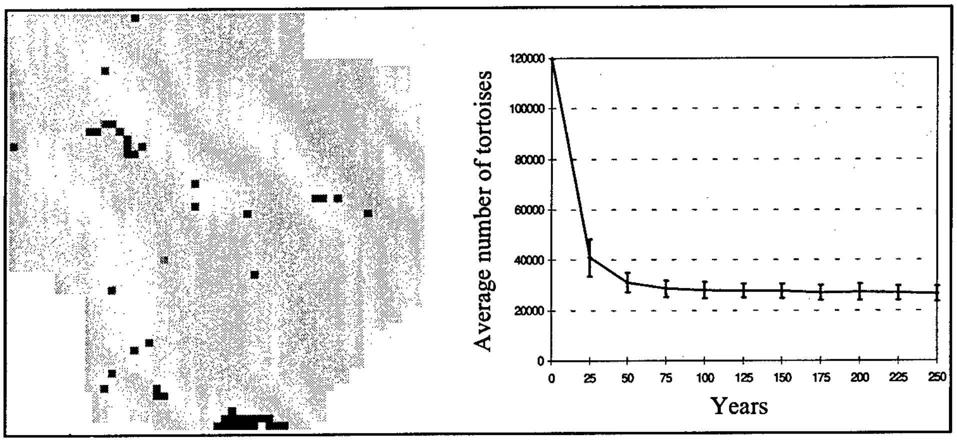

Figure 9. The average spatial distribution of desert tortoises and the change in average number of tortoises after running scenario 3a for 250 years for Fort Irwin. The average was obtained from 100 simulations of scenario 3a. Scenario 3a used Figures 4 and 5a as initialization maps for tortoise density and vegetative cover, respectively. On a monthly basis, a low level of training occurred in the model after time step 0. Darker shades represent higher tortoise densities.

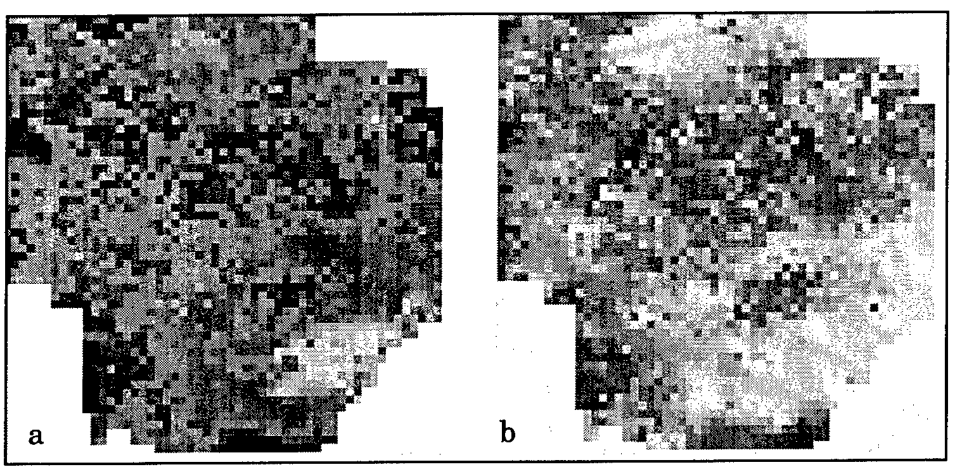

Figure 10. The average percent aerial cover of vegetation (a) and average index of habitat suitability (b) for desert tortoises after running scenario 3a for 250 years for Fort Irwin. The average was obtained from 100 simulations of scenario 3a. Figures 5a and 6b show the average percent aerial cover of vegetation and index of habitat suitability, respectively, at time 0 for scenario 3a. No new training occurred in the model after time step 0. Darker shades represent higher densities of vegetative cover (a) and habitat better suited for tortoises (b).

Scenario 3b: Moderate Training Intensity

Scenario 3b was identical to scenario 3a except that the training level was moderate (832.5 TVD/month), rather than low intensity. The same initialization maps for tortoise density and vegetation from scenarios 2 and 3a were used (Figures 4 and 5a, respectively).

In each of 100 runs, the tortoise population became extinct within 25 years (Figure 11). The vegetation and habitat suitability also decreased during moderate training (Figure 12). The results indicate that tortoises and

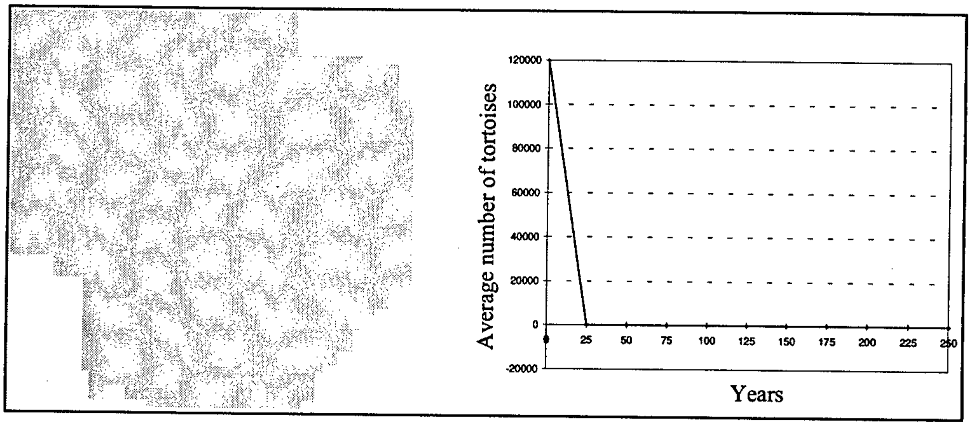

Figure 11. The average spatial distribution of tortoises and the change in average number of tortoises after running scenario 3b for 250 years for Fort Irwin. The average was obtained from 100 simulations of scenario 3b. Scenario 3b used Figures 4 and 5a as initialization maps for tortoise density and vegetative cover, respectively. On a monthly basis, a moderate level of training occurred in the model after time step 0.

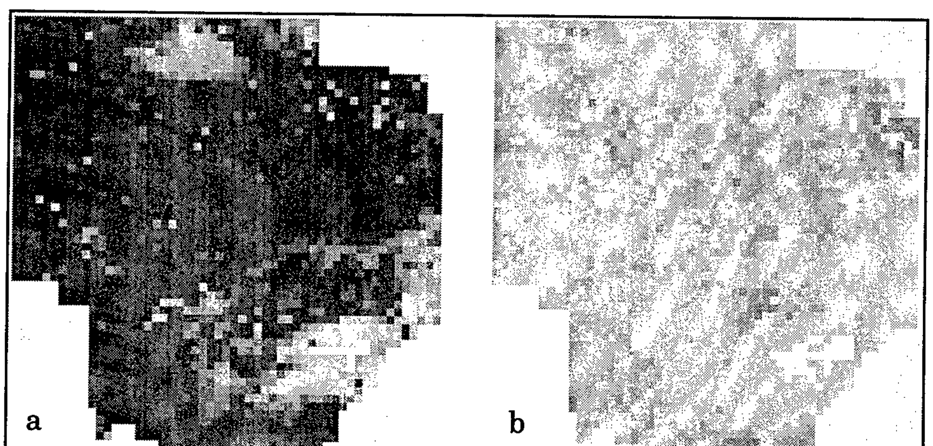

Figure 12. The average percent aerial cover of vegetation (a) and average index of habitat suitability (b) for desert tortoises after running scenario 3b for 250 years for Fort Irwin. The average was obtained from 100 simulations of scenario 3b. Figures 5a and 6b show the average percent aerial cover of vegetation and index of habitat suitability, respectively, of time 0 for scenario 3b. On a monthly basis, a moderate level of training occurred in the model after time step 0. Darker shades represent higher densities of vegetative cover (a) and habitat better suited for tortoises (b).

vegetation were unable to withstand moderate levels of training over extended periods. At this level of training, the vegetation had no time to recover. Studies have indicated that soil and vegetation recovery in desert environments can take more than 100 years depending on the severity of the impacts (Webb and Wilshire 1980).

Given the results of this scenario, the model was not run with higher intensity training, as vegetation and tortoises would have been even more severely impacted.

Scenario 4: Training Varied Temporally

This scenario examined the responses of tortoises and vegetation to seasonal rather than sustained training activities. Tortoises display seasonal patterns by hibernating November through February and breeding and laying eggs March through October (Luckenbach 1982). These seasonal patterns were incorporated into the training activities, so that moderate intensity training occurred November through February (while the tortoises hibernated) and low intensity training occurred March through October (while tortoises were active). While seasonal training activities were based on tortoise activities, direct impacts of training on tortoises (e.g., being crushed in their burrows) were not included in the model. However, the indirect impacts of training occurring on a seasonal basis were expected to allow vegetation to recover from impacts and result in increased habitat suitability for tortoises. The egg-laying and nesting season is a critical time for tortoises, and adequate vegetative cover may be especially important at these times (Krzysik 1994).The initialization maps for tortoise density and vegetation were the same used for scenario 2 (Figures 4 and 5a, respectively). Training occurred at each time step (monthly), but training intensity was moderate (832.5 TVD/ month) November through February and low (237.5 TVD/month) March through October over all of Fort Irwin.

After running the model for 250 years, the tortoise population asymptotically decreased and became very patchily distributed across the landscape (Figure 13). The aerial cover of vegetation and habitat suitability also decreased (Figure 14). These results were very similar to the results of scenario 3a (constant low intensity training), which suggested that tortoises and vegetation were able to withstand periodic moderate training, but not constant moderate training (see scenario 3b), throughout the year. The low level of training during March through October allowed the vegetation adequate time to recover, which indirectly allowed tortoise populations to remain stable. In short, seasonal military training caused the tortoise population to decline initially, but it stabilized after the first 50 years.

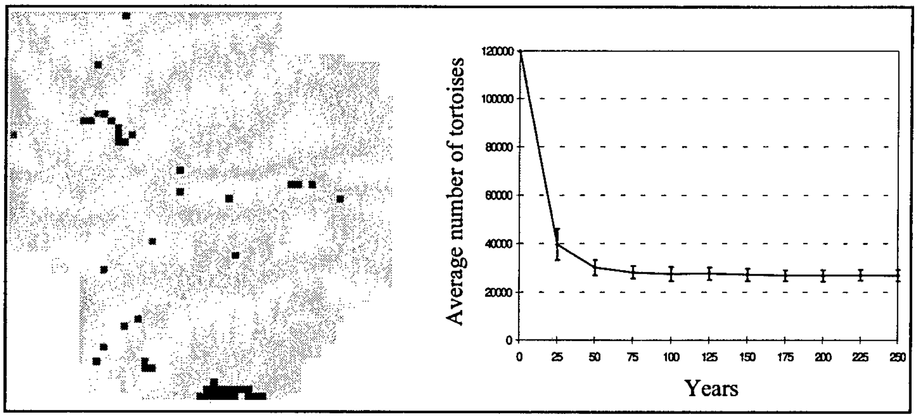

Figure 13. The average spatial distribution of tortoises and the change in average number of tortoises after running scenario 4 for 250 years for Fort Irwin. The average was obtained from 100 simulations of scenario 4. Scenario 4 used Figures 4 and 5a as initialization maps for tortoise density and vegetative cover, respectively. Temporal variation of training occurred during scenario 4. Darker shades represent higher tortoise densities.

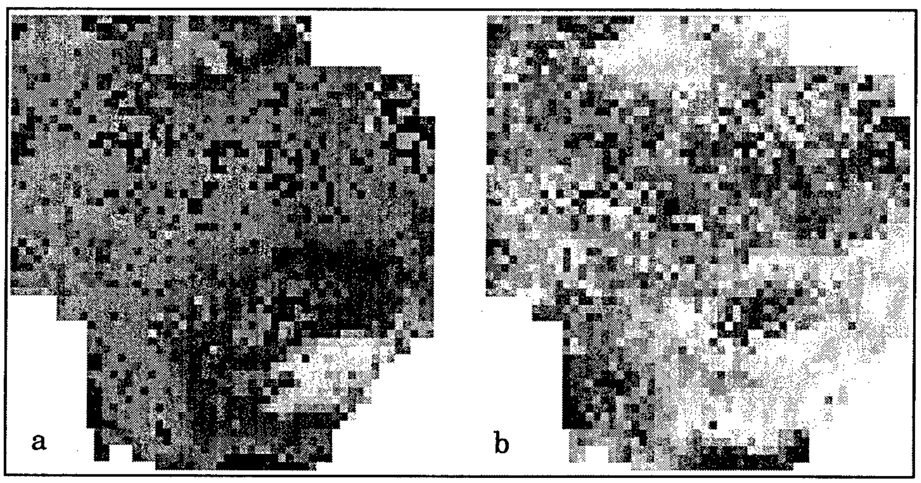

Figure 14. The average percent aerial cover of vegetation (a) and average index of habitat suitability (b) for desert tortoises after running scenario 4 for 250 years at Fort Irwin. The average was obtained from 100 simulations for scenario 4. Figures 5a and 6b show the average percent aerial cover of vegetation and index of habitat suitability, respectively, of time 0 for scenario 4. Temporal variation of training occurred during scenario 4. Darker shades represent higher densities of vegetative cover (a) and habitat better suited for tortoises (b).

Scenario 5: Training Varied Spatially

In the previous scenarios, training occurred with similar intensity in all cells across Fort Irwin. However, training likely occurs at different intensities across the installation with approximately 64 percent of the total installation available for military training (Goran, Radke, and Severinghaus 1983). In this scenario, an attempt was made to capture spatial variation in training intensity. Training intensity was assumed to be related to elevation, with most training occurring in lower elevations (Krzysik 1994). Three levels of training intensity were used; low (237.5 TVD/month), moderate (832.5 TVD/month), and high (1428 TVD/ month). The training occurred in the lower elevations toward the center of the simulated landscape (Figure 2a). No training occurred on the remaining portion of the landscape. The initialization maps for tortoise density and vegetative cover were the same used for scenario 2 (Figures 4 and 5a, respectively). Training occurred at each time step (i.e., monthly), and varied spatially based on the training map (Figure 2b). Temporal variation was not included in this scenario.

Results of this scenario indicated that the tortoise population asymptotically decreased, but the amount of decline was much less than in previous scenarios (Figure 15). Spatially, tortoises did not occur where training occurred. Vegetation and habitat suitability also decreased (Figure 16), but not to the same extent as found in previous scenarios. Both the vegetation and habitat suitability were impacted in areas where training occurred, but appeared to do well outside of those areas. This observation suggested that areas with suitable tortoise habitat, which were restricted from training exercises, supported tortoises for long periods of time.

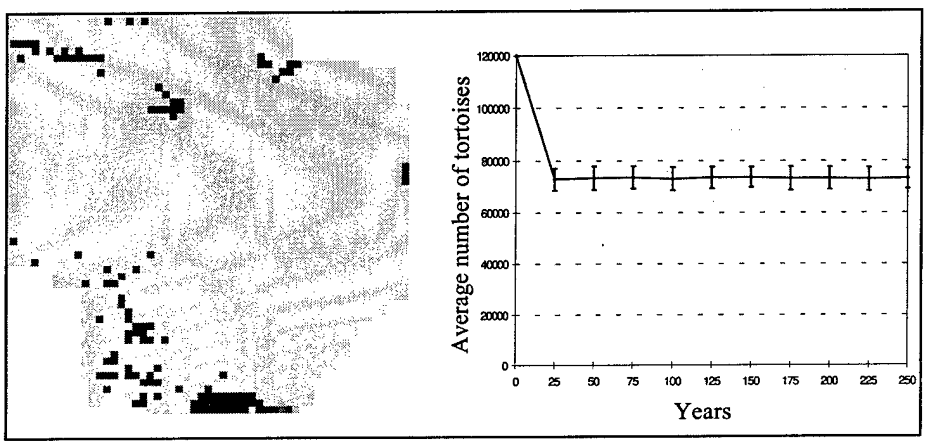

Figure 15. The average spatial distribution of tortoises and the change in average number of tortoises after running scenario 5 for 250 years at Fort Irwin. The average was obtained from 100 simulations of scenario 5. Scenario 5 used Figures 4 and 5a as initialization maps for tortoise density and vegetative cover, respectively. Spatial variation of training occurred during scenario 5. Darker shades represent higher tortoise densities.

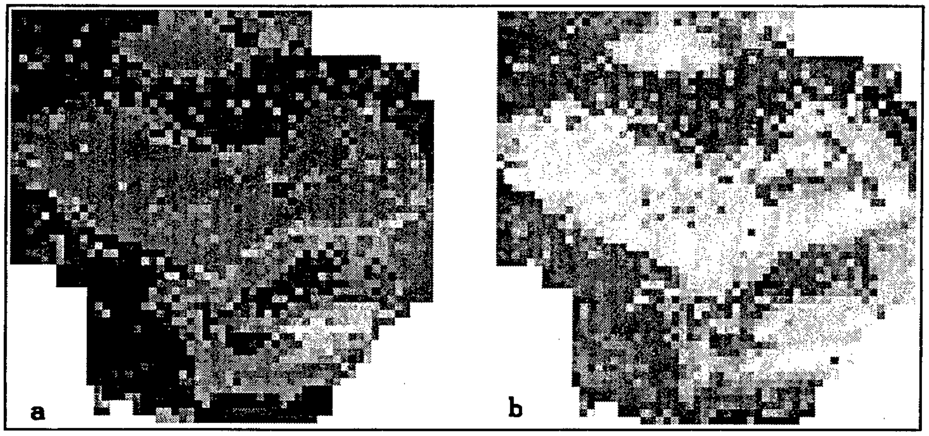

Figure 16. The average percent aerial cover of vegetation (a) and average index of habitat suitability (b) for desert tortoises after running scenario 5 for 250 years at Fort Irwin. The average was obtained from 100 simulations of scenario 5. Figures 5a and 6b show the average percent aerial cover of vegetation and index of habitat suitability, respectively, of time 0 for scenario 5. Spatial variation of training occurred during scenario 5. Darker shades represent higher densities of vegetative cover (a) and habitat better suited for tortoises (b).

Scenario 6: Training Varied Temporally and Spatially

Realistically, military training at Fort Irwin likely occurs at different intensities over both time and space. To simulate such variation in intensity, scenario 5 was modified to include only two training intensities (low and moderate) for each of the two seasons identified in scenario 4 (Figure 17). The same initialization maps for tortoise density and vegetative cover from scenario 2 were used (Figures 4 and 5a, respectively). Thus, training occurred at each time step (i.e., monthly), but varied spatially.

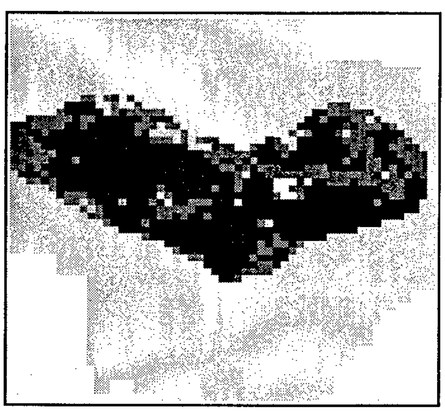

Figure 17. Training intensity map for scenario 6, Fort Irwin. Training was excluded from the most lightly shaded areas. The moderately shaded areas were subject to low training intensity while the darkest shaded areas indicated moderate training intensity.

The tortoise population decreased, but not to the same extent as in previous scenarios (Figure 18). Spatially, the tortoises did not occur where training occurred. Woodman et al. (1986) found high tortoise densities near areas with high training impacts, but each area was mutually exclusive of the other. The aerial cover of vegetation and habitat suitability also decreased in scenario 6, but also not to the same extent as in previous scenarios (Figure 19).

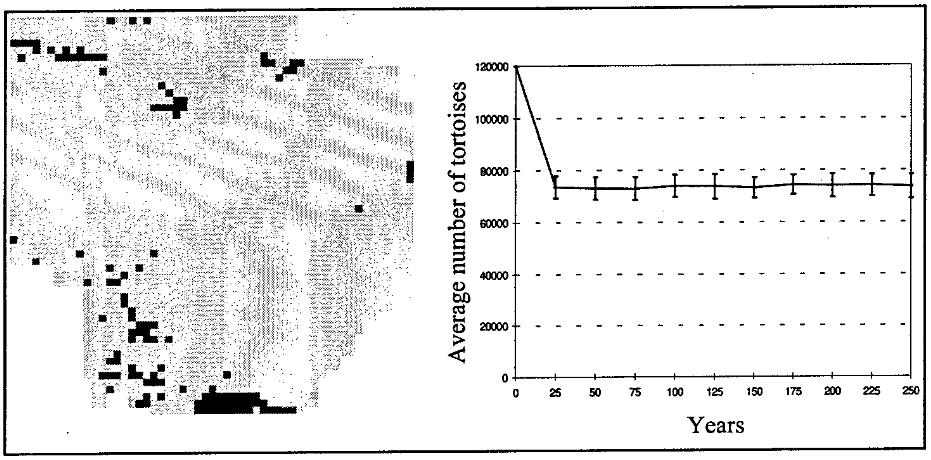

Figure 18. The average spatial distribution of tortoises and the change in average number of tortoises after running scenario 6 for 250 years for Fort Irwin. The average was obtained from 100 simulations of scenario 6. Scenario 6 used Figures 4 and 5a as initialization maps for tortoise density and vegetative cover, respectively. Spatial and temporal variation of training occurred during scenario 6. Darker shades represent higher tortoise densities.

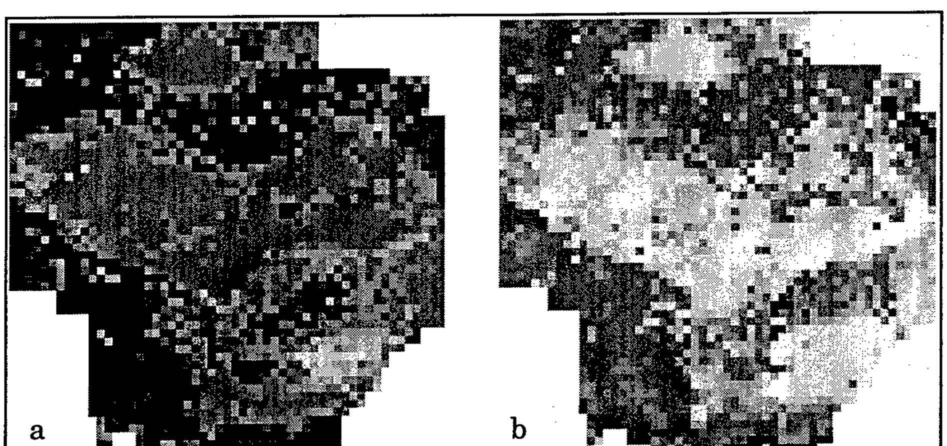

Figure 19. The average percent aerial cover of vegetation (a) and average index of habitat suitability (b) for desert tortoises after running scenario 6 for 250 years at Fort Irwin. The average was obtained from 100 simulations of scenario 6. Figures 5a and 6b show the average percent aerial cover of vegetation and index of habitat suitability, respectively, of time 0 for scenario 6. Spatial and temporal variation of training occurred during scenario 6. Darker shades represent higher densities of vegetative cover and habitat better suited for tortoises.

Results of this scenario were very similar to those of scenario 5, suggesting that the spatial variation in training intensity had a stronger influence on tortoise populations than did temporal variation. Thus, the model predicted that the effects of temporal and spatial variation in training intensity on tortoise population dynamics were not additive.

Comparisons Among Scenarios 1-6

To compare the results of all scenarios, the percent difference between the average tortoise population in year 250 for different pairs of scenarios was determined (Table 1). Only a 2 percent difference resulted between the final tortoise populations in scenarios 1 and 2, indicating that a steady state in the model was obtained at the end of scenario 1 and maintained throughout scenario 2. This suggested that the landscape had recovered from past impacts. Comparisons between the final tortoise population in scenario 2 (no training) with scenarios 3 through 6 (with training) indicated that simulated military training impacted tortoise dynamics. However, some training scenarios impacted tortoises far more or less than others.

The simulations indicated that low intensity training affected the tortoise population much less than moderate intensity training. Further, periodic moderate intensity training (scenario 4) had effects similar to constant low intensity training (scenario 3a), suggesting that timing of training can influence tortoise populations. Temporal variation in training intensity likely would have had an even greater affect on tortoises if direct effects had been incorporated into the model, because of the seasonal differences in tortoise activities.

Table 1. Percent difference between scenarios of the desert tortoise population after running the model for 250 years at Fort Irwin.

Scenarios[a]	2	3a	3b	4	5	6
1	+2	-78	-100	-78	-39	-38
2		-78	-100	-78	-40	-40
3a			-100	+1	+64	+64
3b				+100	+100	+100
4					+63	+64
5						+1

[a]Scenario descriptions:

1: neural network baseline

2: new baseline

3a: low intensity training

3b: moderate intensity training

4: training varied temporally

5: training varied spatially

6: training varied temporally and spatially

Spatial variation of training impacted the tortoise population less than most other scenarios. Scenario 6 represents the most realistic training scenario because it incorporates both timing and location of training. Results of this scenario indicated that impacts on tortoises may be minimized by altering the timing, location, and intensity of training. Additional data on patterns and timing of training are needed for future modeling efforts.

Scenario 7: Potential Tortoise Reintroduction

This scenario used the model to determine if areas on Fort Irwin might serve as sites for potential reintroduction of tortoises. In all the previous scenarios, tortoises occur in certain areas of Fort Irwin, but not in others. This pattern held throughout all simulations, perhaps because of limited movement away from initial locations into suitable habitat. Are there additional areas on the simulated landscape that are suitable for tortoises but remained unoccupied in previous scenarios?

The initialization map for vegetation from time 250 years of scenario 1 was used to answer this question. Each cell across the Fort Irwin landscape was initialized with the maximum number of tortoises that occurred in scenario 1 at 250 years (415 female tortoises/km^2). In this scenario, the total number of tortoises on Fort Irwin was artificially high. This simulation was run with no new training after time 0, allowing tortoises to move around on the landscape without any impacts from training.

The results (Figure 20) indicated a dramatic drop in the tortoise population in the first 25 years. Since no impacts were incorporated into this scenario, the drop was attributed to an artificially large number of tortoises, which the landscape could not support. After the initial drop, the population stabilized at a higher level than in previous scenarios. Comparison of these results (Figure 20) with the results of scenario 2 (Figure 7) indicated areas in which tortoises could be supported but do not currently occur. Thus, errors in the initialization map for tortoise density, which was used to initialize the other scenarios, may have influenced the results.

The vegetation and the habitat suitability index results (Figure 21) were very similar to the results of scenario 2 (Figure 8). This similarity was expected because no new training occurred after time 0.

Even though the model indicated potential reintroduction sites on Fort Irwin, additional criteria need to be considered before pursuing a tortoise reintroduction. Berry (1986) suggested that relocation sites should be at least 14 km in diameter to permit dispersal, and introduction sites should be into areas where tortoises were recently extirpated to ensure suitable habitat exists. Further research is needed to determine if the areas indicated in the model meet these criteria.

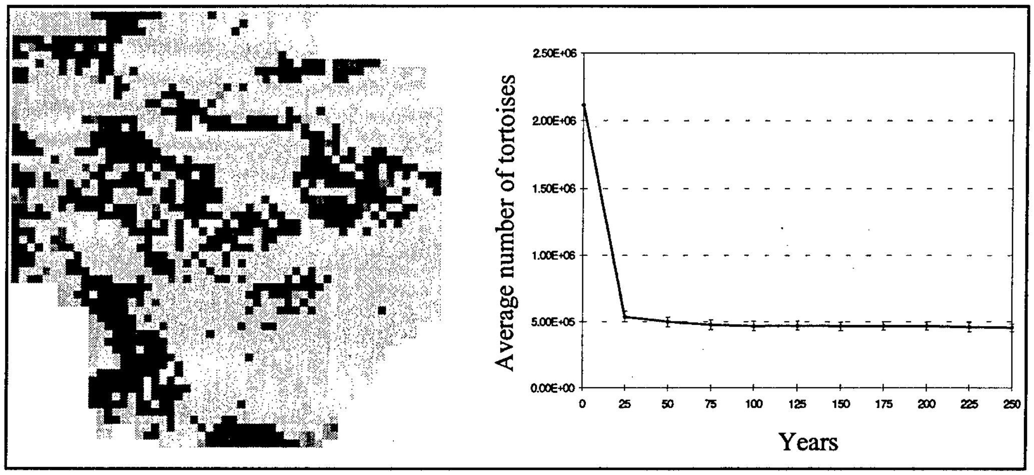

Figure 20. The average spatial distribution of tortoises and the change in average number of tortoises after running scenario 7 for 250 years for Fort Irwin. The average was obtained from 100 simulations of scenario 7. Scenario 7 used Figures 4 and 5a as initialization maps for tortoise density and vegetative cover, respectively. The desert tortoise population was artificially high because tortoises were placed in every cell on the Fort Irwin landscape. Darker shades represent higher tortoise densities.

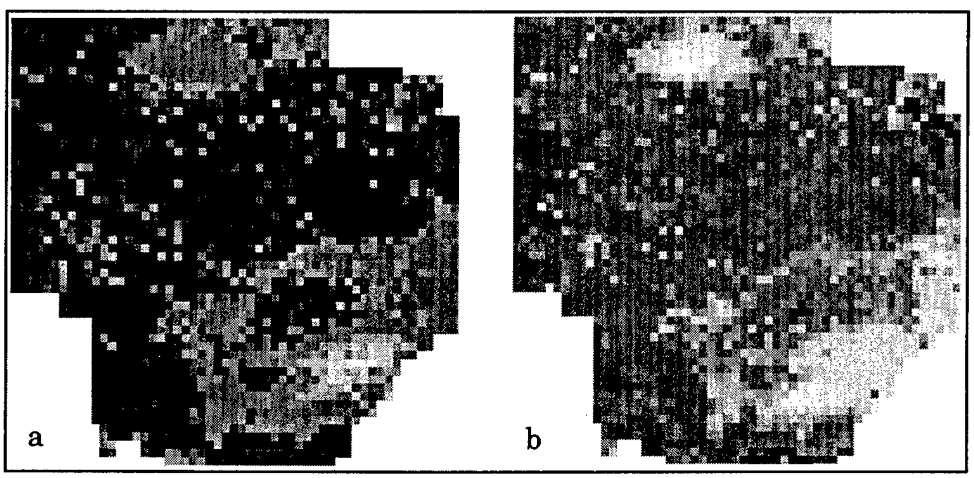

Figure 21. The average percent aerial cover of vegetation (a) and average index of habitat suitability (b) for desert tortoises after running scenario 7 for 250 years at Fort Irwin. The average was obtained from 100 simulations of scenario 7. Figures 5a and 6b show the average percent aerial cover of vegetation and index of habitat suitability, respectively, of time 0 for scenario 7. Darker shades represent higher densities of vegetative cover (a) and habitat better suited for tortoises (b).

3 Conclusions

This research focused on two objectives: (1) demonstrate the usefulness of DLS for military installation management and (2) evaluate the application of a DLS based on the Fort Irwin landscape.

The DLS Approach

To effectively manage landscapes, the implications of alternative management strategies on a natural system must be understood with regard to both temporal and spatial variation. Scientific understanding of how components of the landscape interact over time have resulted in models of overland water flow, groundwater, community succession, weather and climate, vegetative growth, and habitat suitability. Such models have not been fully useful to land managers because each model dynamically views only a portion of the whole system, while holding the rest of the system constant.

This simulation effort demonstrated a new class of management tools that allows land managers to create DLS systems. These systems draw static information from local GIS databases and dynamic information is exchanged among cells on the landscape at each time step. New power in affordable computers ensures a dramatically improving cost to benefit ratio associated with the design, development, and application of DLS.

SME allows nonprogrammers to develop complex models using the STELLA modeling desktop tool. Such tools may become common in military installation environmental offices.

The Model

Desert tortoises are a long-lived species with a low reproductive rate, making them vulnerable to perturbation (Woodman et al. 1986). They depend on perennial shrubs for cover and burrow sites. Because tortoises are vulnerable to impacts on their environment, it is valuable to have a model that can gauge the effects of impacts on their population density and habitat.

A spatially explicit model was developed to evaluate potential effects of military training on desert tortoises and their habitat at Fort Irwin. While results were not expected to provide land managers with detailed predictions of specific impacts, the feasibility of using this modeling technique to develop landscape-level simulation models was demonstrated.

Spatially explicit models can be applied to the management of threatened and endangered species (TES). Often, a major factor in a species decline is habitat loss and fragmentation over the species range. Spatially explicit models developed at the landscape level could provide new management techniques for TES survival. Our modeling approach (developing a single-cell model, initializing it with GIS maps, and then running the model to simulate changes across the landscape) proved successful for desert tortoises at Fort Irwin. This approach can be used to develop future, realistic models for other species and landscapes.

While models can aid in the synthesis of many parts into a whole, modeling cannot be substituted for field experimentation (Salwasser 1986; Conroy et al. 1995). Future model development should include obtaining more accurate tortoise dispersal and military training data. Furthermore, additional simulation scenarios could be conducted to determine if there are optimal spatial and temporal patterns for different levels of military training, which will minimize impacts on tortoises and vegetation.

Land managers must not expect models to make decisions for them or to provide them with a perfect version of a real-world system (Chalk 1986). For modeling technology to reach its full potential in TES management, researchers and managers must work together. This cooperation will aid researchers in understanding the needs of managers and will provide managers with a sense of ownership in the models they use (Chalk 1986).

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